Genetic Algorithm Tuned PI Controller on PMSM Direct Torque Control

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Article Info

ABSTRACT

This paper presents the Direct Torque Control (DTC) strategy for the Permanent Magnets Synchronous Machine (PMSM) with tuning the PI controller by using genetic algorithms to ensure optimal performance it allows reducing the ripples of the torque and flux. A genetic algorithm is used to optimize the gains of the PI controller for given the reference of the torque. Simulation results verified the performance of the proposed approach. The simulations result of this technique is justified the minimization the ripples of switching in the inverter and reduces the harmonious of the torque and the stator current.

Keywords:
Permanent Magnet Synchronous Machine (PMSM), DTC, Genetic Algorithm (GA), voltage inverter

I. Introduction

Permanent Magnet Synchronous Machines (PMSMs) are widely used in many industrial production systems and attractive candidates for high-performance applications due to their high efficiency, high torque mass ratio, and ease to be controlled [1,2]. PMSMs are mainly applied when the system requires fast torque response and best performance such as in the wind power industry, especially for direct-driven wind turbine applications, due to capability of multiple-pole design [3], and railway traction application, in order to achieve the PMSM start-up at standstill or at very low speeds [4]. Many studies have been developed to find out different solutions for reducing the complexity of Field Oriented Control (FOC), several approaches are used, such as the Direct Torque Control (DTC) strategy that is insensitive to the motor parameters variation [5, 6]. The DTC was proposed by Takahashi and Depenbrock in the middle of the 1980s, for driving the induction motors [4,5], the application of DTC to permanent magnet synchronous machines (PMSMs) was presented in the late 1990s [7]. The DTC control is based on an appropriate choice of voltage vector generated by the inverter. It has several advantages compared to other conventional techniques, such as a fast dynamic torque, robustness with respect to parameter variations, a simple control with low-cost computing efforts because it does not need the complex coordinate transformation, and the possibility to control the torque independently from the flux, the rotor position sensor is not required, reduced computations. [8,9,10,11,6]. The DTC, however; has the inherent problem of varying switching frequency with constant hysteresis bands, which is undesired for some applications [12]. This problem of the DTC control has generated some new research interests in the field of electrical drives. In particular, several techniques have been carried out to reduce the flux and torque ripples released by an inverter. A popular solution is to increase the number of available voltage vectors, following
that idea, a multilevel inverter, and a discrete space vector modulation (DSVM) technique which divided each control period into three intervals, or using fairly low sampling frequencies [13]. Other researches have focused on Space Vector Modulation (SVM) to achieve constant switching frequency while obtaining the desired torque and stator flux in one control period by synthesizing a suitable voltage vector through SVM [7,14], or using the DTC-SVM with a sliding mode control [15]. On other hands, there exist a solution based on the technique of artificial intelligence such as Artificial Neural Network (ANN) in [14], Fuzzy Logic Controller (FLC) in [16], Particle Swarm Optimization (PSO) and Genetic Algorithms (GA). The controller PI is used to control the speed due to simple structure; however, tuning the accurate parameters of PI controller is a hard task, where these parameters are necessary to improve the performance of the DTC control. To enhance the issue of conventional PI parameter tuning techniques many research has been suggested as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA). This work proposes to control the speed of a PI controller optimized by using the Genetic Algorithms (GA) to provide the performances of direct torque control. GA is general-purpose optimization techniques that use a direct analogy of natural evolution where stronger individuals would likely be the winners in a competing environment. Efficacy of GA as an optimization tool has already been observed in process control [14]. In this work, GA is used to optimize the motor’s speed for minimized the ripple of the torque and the flux. This paper is organized as follows. In section II, PMSM is presented. Section III, describes the principle of DTC. In section IV, the implementation of a genetic algorithm (GA) is used in tuning the PI controller parameters of speed. In Section V, simulation results and discussion are presented. Conclusions are summed up in the last section;

II. PMSM Modeling

The continuous time model for PMSM in the d-q coordinate system can be described as:

Currents equations [14]:

\[
\begin{align*}
\frac{di_d}{dt} &= \frac{1}{L_d} \left( u_d - R_s i_d + \omega L_q i_q \right) \\
\frac{di_q}{dt} &= \frac{1}{L_q} \left( u_q - R_s i_q + \omega L_d i_d - \omega \varphi_f \right)
\end{align*}
\]  

(1)

Stator flux equations:

\[
\begin{align*}
\varphi_d &= L_d i_d + \varphi_f \\
\varphi_q &= L_q i_q
\end{align*}
\]  

(2)

Electromagnetic Torque equation:

\[
T_{em} = \frac{3}{2} p \left[ (\varphi_f i_q + (L_d - L_q)) i_d i_q \right]
\]  

(3)

The mechanical equation

\[
J \frac{d\Omega}{dt} + f\Omega = T_{em} - T_r
\]  

(4)

where \( R_s \) is stator resistance, \( i_d \) and \( i_q \) are stator currents in d-q coordinate system, \( u_d \) and \( u_q \) are stator voltages in d and q axis-components, \( \varphi_d, \varphi_q \) are stator flux, \( \omega \) is the angular speed, \( L_d \) and \( L_q \) are direct-axis, and quadrature-axis inductance, \( \varphi_f \) is permanents magnet flux, and \( \Omega, C, f, \) and \( J \) are the speed, load torque, and friction coefficient, and moment of inertia respectively.
III. Principle of DTC

The block diagram of the classical DTC of a PMSM scheme is shown in Fig.1. The basic idea of DTC is to control the electromagnetic torque and the stator flux by selecting one of the voltage vectors generated by a VSI in order to maintain flux and torque within the limits of two hysteresis bands and the right selection of the voltages vector allows a decoupled control for both the flux and the torque without d-q coordinate transformation [15]. The estimated electromagnetic torque and the stator flux are compared with their desired values respectively shown in fig1. The stator flux and torque errors generated by hysteresis comparators are used to deliver the appropriate voltage vector based on the position of stator flux from switching table.

![Diagram of DTC]

Fig.1. The general structure of classic DTC

The voltage vector of the PWM inverter $V_s$ can be defined by three inverter switching states $S_1$, $S_2$ and $S_3$ and the DC link voltage $V_{DC}$ as:

$$V_s = \frac{2}{3}V_{DC} \left[ S_1 + S_2 e^{j2\pi/3} + S_3 e^{j4\pi/3} \right]$$  \hspace{1cm} (5)

The stator flux can be expressed as:

$$\varphi_s(t) = \int_0^t (\dot{V}_s - R_i \dot{I}_s) dt$$  \hspace{1cm} (6)

The magnitude of stator flux linkage given by:

$$\varphi_s = \sqrt{(\varphi_{s\alpha})^2 + (\varphi_{s\beta})^2}$$  \hspace{1cm} (7)

If the voltage drop across the stator resistance is neglected Eq.(6) yields:

$$\varphi_s(t) \approx \varphi_{s0} + \int_0^t V_s dt$$  \hspace{1cm} (8)

With $\varphi_{s0}$ is the initial value of the stator flux.
Eq. (8) could be written in the discrete form as follows:

\[ \varphi_{sk+1} - \varphi_{sk} \approx V_{sk} T_s \]  

(9)

Where \( T_s \) is the sampling time.

This relation means that if the sampling period is constant, the stator flux variation can be directly adjusted by the voltage vector applied to the machine. In the case of the PMSM, the stator flux changes even if we apply a zero voltage when magnets turn with the rotor. Consequently, the non-null voltage vectors are not used in the control of the flux.

The electromagnetic torque is proportional to the vectors of the stator flux and the rotor flux according to the following expression:

\[ T_{em} = \frac{P}{L_d} \varphi_s \varphi_f \sin \gamma \]  

(10)

With \( \gamma \) is the angle between \( \varphi_s \) and \( \varphi_f \).

From this expression, if we maintain the flux constant we can directly control the torque by changing the angle.

The voltage space vector angle is represented in a frame on Fig. 3 and separated in 6 sectors with an index 'k' with k=1,2, 6. When the vector flux is in a sector 'k', then the control of the flux and the torque is assured by selecting one of the four non-zero voltage vectors (V₁ to V₆) or one of the two zero vectors V₀ or V₇ [16,8].

The role of the selected voltage vector is presented in fig.3.

The selected voltage vector is depended with the both hysteresis controllers’ outputs (\( \varepsilon_{\varphi s} \), \( \varepsilon_{Tem} \)) and the sector (\( S \)) of the stator flux. Generally, the stator flux is located in one of the \( k^{th} \) sector. The selection of voltage vectors \( V_{k+1} \) and \( V_{k+2} \) should increase the torque and the vectors \( V_{k-1} \) and \( V_{k-2} \) should decrease it. In addition, the application of \( V_{k+1} \) and \( V_{k+2} \) should increase the stator flux, and \( V_{k-1} \) and \( V_{k-2} \) should decrease it. The application of the zero voltage (\( V_0, V_7 \)) kept the torque in the hysteresis bands [14,17]. The switching table for all the different is shown by Table 1.
Table 1. Switching table of the classic DTC

<table>
<thead>
<tr>
<th>$e_{sv}$</th>
<th>1</th>
<th>0</th>
<th>-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_{Te_m}$</td>
<td>1</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>Sector 1</td>
<td>$V_2$</td>
<td>$V_7$</td>
<td>$V_6$</td>
</tr>
<tr>
<td>Sector 2</td>
<td>$V_3$</td>
<td>$V_0$</td>
<td>$V_1$</td>
</tr>
<tr>
<td>Sector 3</td>
<td>$V_4$</td>
<td>$V_7$</td>
<td>$V_2$</td>
</tr>
<tr>
<td>Sector 4</td>
<td>$V_5$</td>
<td>$V_0$</td>
<td>$V_3$</td>
</tr>
<tr>
<td>Sector 5</td>
<td>$V_6$</td>
<td>$V_7$</td>
<td>$V_4$</td>
</tr>
<tr>
<td>Sector 6</td>
<td>$V_1$</td>
<td>$V_0$</td>
<td>$V_5$</td>
</tr>
</tbody>
</table>

IV. PI Controller Tuning Using GA

Genetic Algorithm (GA) is a stochastic optimization technique based on the mechanisms of natural selection. Compared with other optimization techniques, GA is superior in avoiding local minima which is a common aspect of nonlinear systems. In addition, GA is a derivative-free optimization technique that makes it more attractive for applications that involve nonsmooth or noisy signals. Generally, GA consists of three main stages: selection, crossover, and mutation [21].

- **Selection stage:** The target of this operation is to obtain a mating pool with the fittest individuals selected according to a probabilistic rule that allows these individuals to be mated into the new population.
- **Crossover stage:** this operation is used to generate new individuals or offsprings which acquire good features from their parents.
- **Mutation stage:** represent the last step of the GA that introduces a change in the offspring bit string to generate new chromosomes which may well solve the problem and at the same time avoid the population falling into a local optimal point.

The strategy of GA based on:

- Create initial population
- Evaluate fitness value for each chromosome.
- Perform selection, crossover, and mutation process.
- Test the max generation or min performance index reached.

V. Results and Simulation

The simulations result of the proposed direct torque of the PMSM motor with the PI controller optimized by GA are presented in fig.4.

Fig. 4-a. Show the rotor speed range of PMSM, the machine starts at $t=0.22s$ from the value the reference (0) until $t=0.25s$ achieves the value of speed (100rad/s) by slowly crossing, and follows the reference without errors in the both states transit and steady.

Fig. 4-b presented the electromagnetic torque, where the torque follows the reference value quickly without any errors, and the ripples torque are reduced into the comparison with the classical DTC.

Fig. 4-c illustrated the current, in this figure the current ripples are reduced but the commutation frequency is not controlled.
On the other hand, Table II, establishes the GA tuning PI speed controller, with the parameters. The GA method with the technique found the “optimum” gains is achieved the values $K_p = 1.23129615$, $K_i = 0.73455084$ and $J=142.946447$.

Table 2. The parameters of GA tuning PI speed controller

<table>
<thead>
<tr>
<th>GA</th>
<th>IAE</th>
<th>ISE</th>
<th>ITAE</th>
<th>ITSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_p$</td>
<td>0.61544707</td>
<td>0.68335393</td>
<td>1.23129615</td>
<td>0.61544707</td>
</tr>
<tr>
<td>$K_i$</td>
<td>0.38069398</td>
<td>0.71847131</td>
<td>0.73455084</td>
<td>0.38069398</td>
</tr>
<tr>
<td>$J$</td>
<td>57946.5886</td>
<td>1205298.65</td>
<td>142.946447</td>
<td>66667.5722</td>
</tr>
<tr>
<td>Time (min)</td>
<td>23.75605</td>
<td>23.7602833</td>
<td>24.0023167</td>
<td>23.8325</td>
</tr>
<tr>
<td>OS (%)</td>
<td>0.04979467</td>
<td>0.04872401</td>
<td>0.07113588</td>
<td>0.04979467</td>
</tr>
<tr>
<td>ST (s)</td>
<td>9.80235721</td>
<td>9.80521777</td>
<td>9.77498048</td>
<td>9.80235721</td>
</tr>
</tbody>
</table>

From simulation results, we find the controller PI tuning parameters by using GA give the better performance for instance the torque and current ripples are reduced.
VI. Conclusion

In this paper, the strategy for the speed controller in DTC of PMSM motor is presented, PI controller tuned by a genetic algorithm, for reducing the ripple of the torque and current. The simulations result of this technique is justified the minimization the ripples of switching in the inverter and reduces the harmonious of the torque and the stator current.

References


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